FREQUENCY COMPARISON (H_MASER 140 0809) - (LNEOP-FORb)
For the period MJD 60849 to MJD 60854

The secondary frequency standard LNEOP-FORb has been compared to the hydrogen Maser 140 0809 of the laboratory, during a measurement campaign between MJD 60849 and 60854 (23rd June 2025 – 28th June 2025). The fountain operation covered 68.7 % of the estimation period.

The mean frequency difference at the middle date of the period is given in the following table:

Period (MJD)	Date of the estimation	y(HMaser$_{140\ 0809}$ – FO2Rb)	u_A	u_B	$u_{A/lab}$	$u_{B/lab}$	u_{SecRep}
60849 – 60854	60851.5	-3336.1	3.0	2.5	1.9	0.0	3.4

Table 1: Results of the comparison in 1 x 10^{-16}.

The calibration is made using the recommended value for the ^{87}Rb secondary representation: 6 834 682 610.904 312 6 Hz (22nd CCTF in 2021).
u_B is the ^{87}Rb fountain type B uncertainty.
u_{SecRep} is the recommended uncertainty of the secondary representation (22nd CCTF in 2021).

During the period, the interrogating signal of the FO2-Rb fountain was based on the multiplication of a 1 GHz signal provided by a cryogenic oscillator phase locked to the maser 140 0809. A synthesizer is used to lock the microwave signal to the atomic resonance. The frequency difference between this maser and the fountain is deduced from the average correction applied to the synthesizer.

Average value and statistical uncertainty

The frequency data are averaged over 0.2 day intervals. We then perform a linear unweighted fit to the average data points to determine the average frequency at the middle date of the period, as given in Table 1. The statistical uncertainty u_A is estimated using the Allan variance of the frequency residuals, after removing the drift. We estimate a conservative statistical uncertainty u_A of 3.0×10^{-16}.

We verified the result by applying a second method. We calculated the accumulated phase by integrating the data points, assuming a constant frequency during each segment, and during the dead times of the fountain operation. The average frequency is then obtained by dividing the total accumulated phase by the calibration period duration. The processing has been performed with segments of 0.01, 0.1 and 1 day duration. The results are in agreement with the values given in Table 1 within 2.1×10^{-16}, which is consistent with the estimation of the statistical uncertainty u_A and the uncertainty due to the link.

LTE 61, avenue de l'Observatoire 75014 Paris – France tél 33 (0)1 40 51 22 04 Unité Mixe de recherche du CNRS 8255,
https://lte.obspm.fr, auteur Michel Abgrall 07/07/2025

Accuracy

The frequency is corrected from the quadratic Zeeman, the black body radiation, the cold collision (+ cavity pulling), the distributed cavity phase shift and the microwave lensing shifts, and at last the redshift. The cold collision (+ cavity pulling) correction is based on alternating measurements at full density for 50 cycles and at half density for 100 cycles, by changing the state selection frequency and readjusting the microwave power to keep the selection transition probability at maximum. The uncertainty in this correction is mostly statistical. The following table summarizes the budget of the systematic corrections and their associated uncertainties. The accuracy is the quadratic sum of all the systematic uncertainties.

	Correction (10^{-16})	**Uncertainty (10^{-16})**
Quadratic Zeeman effect	-3513.45	0.70
Black body radiation	124.26	1.45
Cold collisions + cavity pulling	9.17	0.92
Distributed cavity phase shift	-0.35	1.00
Microwave lensing	-0.70	0.70
Microwave spectral purity&leakage	0	<0.50
Ramsey & Rabi pulling	0	<0.10
Second order Doppler effect	0	<0.10
Background gas collisions	0	<1.00
Total	-3381.07	2.49
Redshift	- 65.45	0.25
Total with redshift	**-3446.52**	**2.50**

Table 2: Budget of systematic effects and uncertainties for LNEOP-FO2Rb fountain for the MJD 60849 – 60854 period

$$\boxed{u_B = \mathbf{2.5 \times 10^{-16}}}$$

Uncertainty of the link

The statistical uncertainty of the link $u_{A/lab}$ is the quadratic sum of 2 terms:
-A possible effect of phase fluctuations introduced by the cables that connect the frequency standard to the maser. A new characterization of the signal distribution leads to a still conservative value of 0.5×10^{-16}.
-The uncertainty due to the dead times of the frequency comparison.
We have updated the estimation of this contribution, applying the method described in *Metrologia*, vol. 44, pp 91-96, 2007, as we did for the initial calibration reports of the LNE-SYRTE Strontium SFS. The maser noise model includes a white frequency noise component of 5×10^{-16} at 1 d and a flicker frequency noise component of 5×10^{-16} at 1 d, which is pessimistic especially for short averaging periods. We applied the method to the dead times longer than 60 s and obtained a stability degradation of 1.8×10^{-16}.

In the signal distribution chain between the maser and the fountain, all the intermediate oscillators are phase locked using proportional/integrator phase lock loops. The comparison between the maser and UTC(OP) is performed using a time interval counter. Therefore, the systematic uncertainty of the link $u_{B/lab}$ is expected to be negligible.